Creating a multifunctional composite stator slot material system to enable high power density electric machines for electrified aircraft applications

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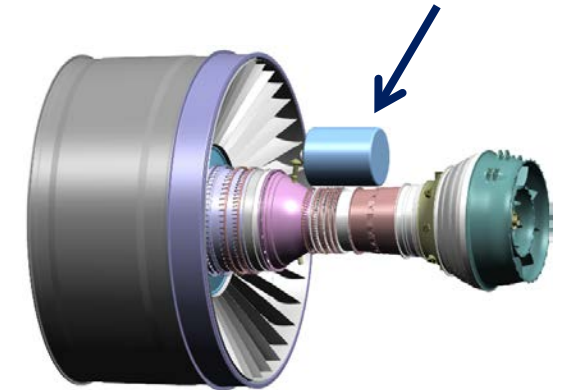Cincinnati, Ohio

Electric Machine Motivation: STARC-ABL

Conventional tube and wing design along with minimal battery dependence makes this a near term possibility (2030ish)

UTRC Concept for HGEP Thermal Management
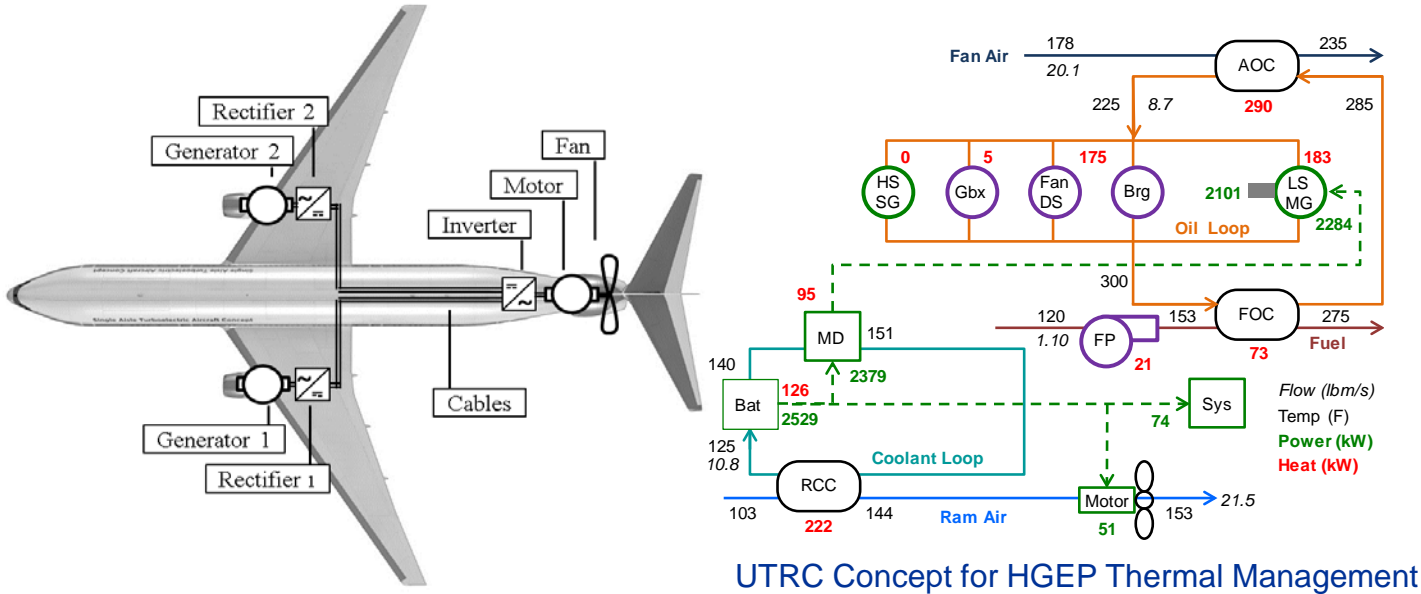
Cooling Loop	Max Temp		
	°C	°F	K
Coolant	60	140	333
Oil	135	275	408

High Power Density Electric Machine

UTRC concept for Hybrid Geared Turbofan

Electrical Machines

- Two 1.4 MW generators mounted near turbines
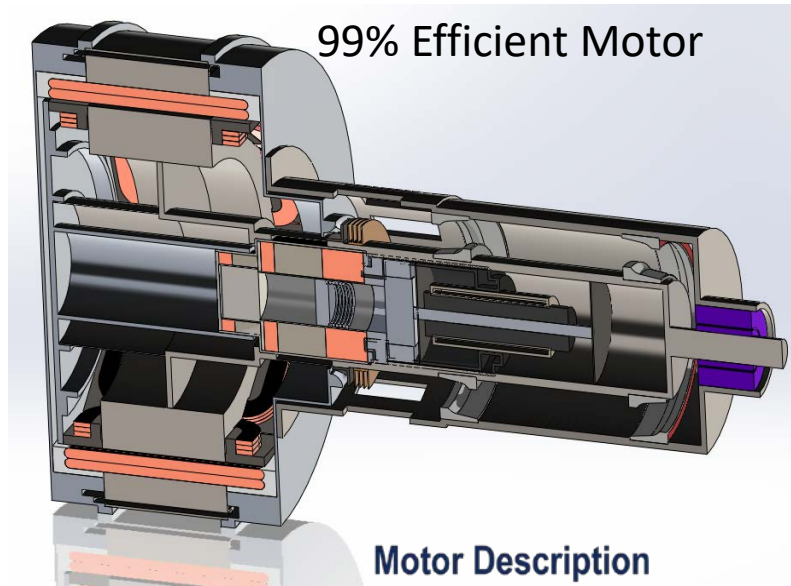- One 2.6 MW motor driving tail cone thruster

Geared Turbofan

- HP Spool = ? rpm
- LP Spool = 6800 rpm (generator connects here)
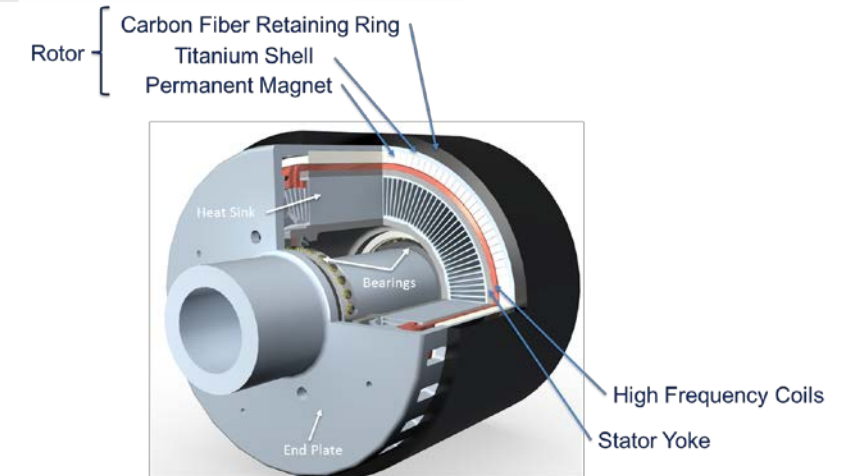
Tailcone Thruster

- Fan = 2514 rpm
- Diameter = 80.2"
- Hub/Tip Ratio = 0.3
- Hub Diameter = 24.1"

Electric Machine Motivation: NASA Efforts

- Internal NASA motor development
  - Target >98% Efficiency Stretch Goal 99%
  - 16 kW/kg
  - 1.46 MW

- External NASA funded motor development
  - >13 kW/kg
  - >1 MW
  - >96% Efficient
  - Teams at UIUC & OSU

- All teams have chosen Litz wire or form wound conductors to meet their goals

- High power densities = higher temperatures = more loss (10 ^{o}C increase in temperature is a 3.9% increase in resistive loss)

99% Efficient Motor

Motor Description

Rotor — Carbon Fiber Retaining Ring / Titanium Shell / Permanent Magnet

Heat Sink
Bearings
End Plate
High Frequency Coils
Stator Yoke

NASA NRA: High Power Density Motor Under Development by Professor Haran's Group, University of Illinois Urbana-Champaign. Contracting Officer Representative Andrew Provenza, NASA Glenn Research Center

Litz Wire

nylon serve

Nomex serve

Copper Litz wire wound on a 1/3 of a
full scale stator model
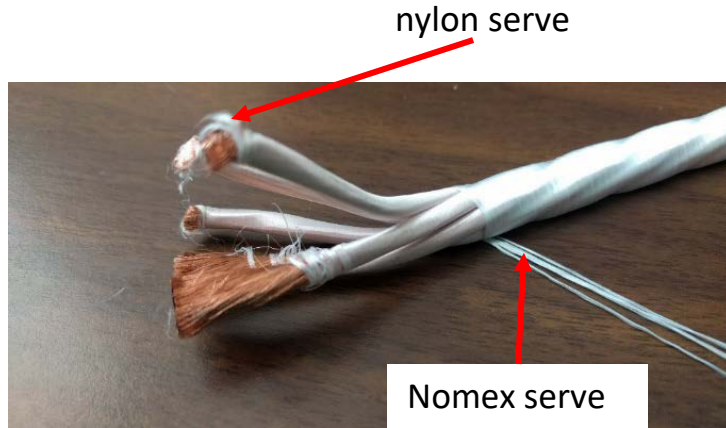
- Litz wire reduces losses due to induced eddy currents
- Parallel conduction of current in the motor-strands at roughly the same potential
  - Standard magnet wire electrical insulation on each strand is a significant over design
- Litz wire offers a unique design space for new material solutions

Inside a Stator Slot

HV Insulation
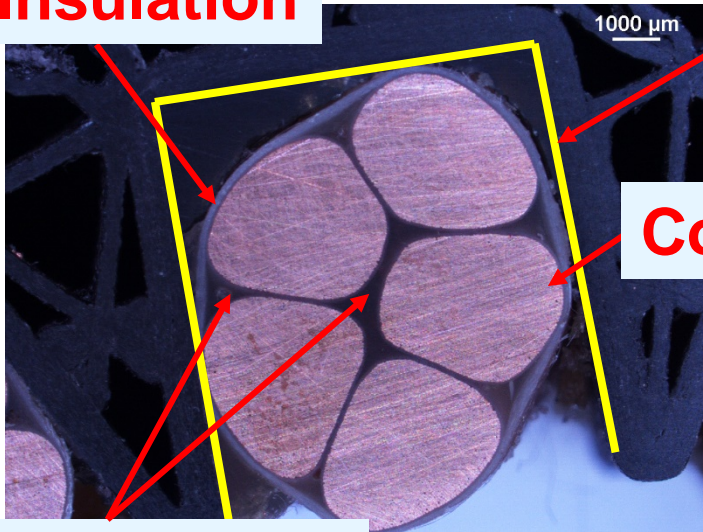
Slot

Conductor

Potting Material

Slot
- soft magnetic material

Wire insulation
- electric isolation, polyimde ~0.1 W/m-K

HV Insulation
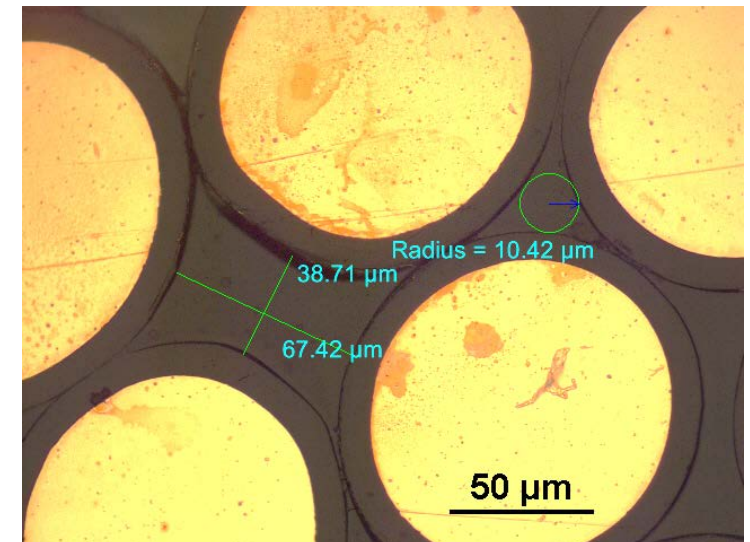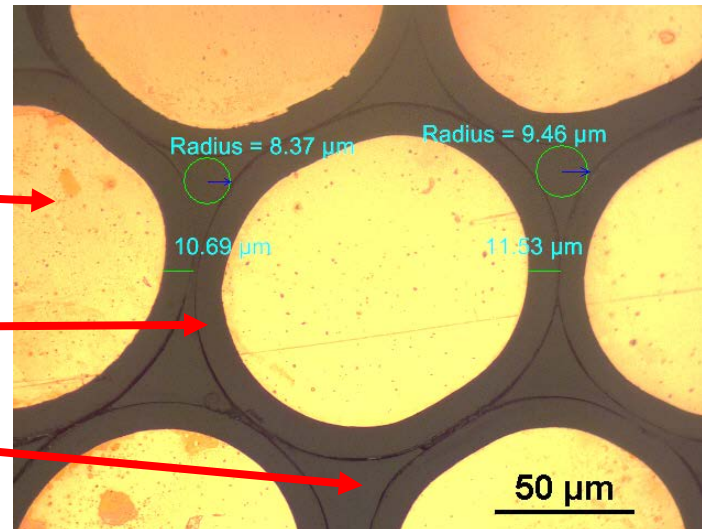- electrical isolation, polyamide or mica (1-2W/m-K)

Potting material
- mechanical stabilization/thermal management*
- epoxy ~2W/m-K (with some exceptions)
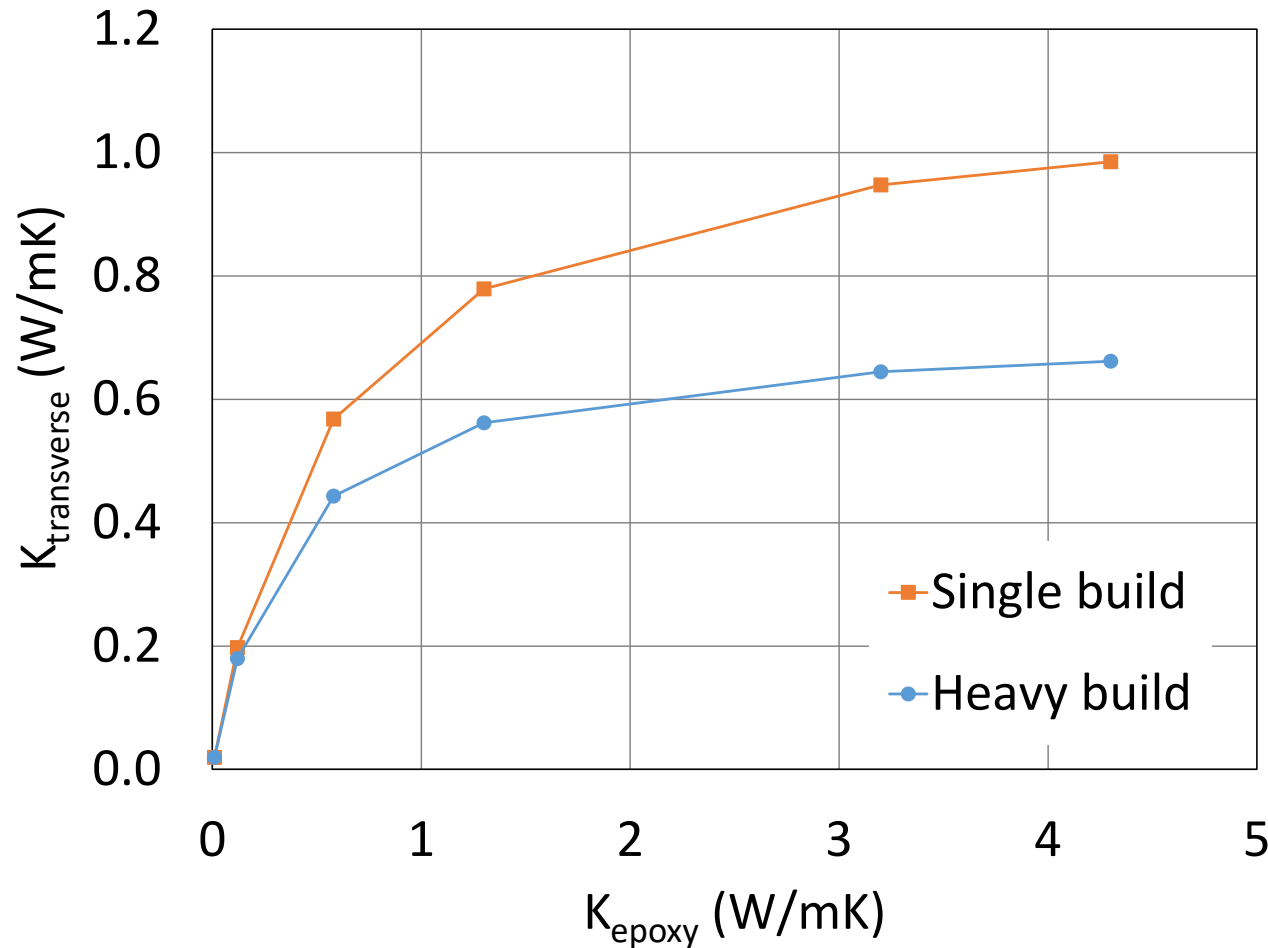

conductor

wire insulation

potting material

Potted AWG 38 (101 micrometer diameter) with a heavy build polyimde insulation

Thermal Effects: Potting Material vs. Wire Insulation


From the law of mixtures

$$K_{transverse} = \cfrac{1}{\cfrac{\eta_{Cu}}{K_{Cu}} + \cfrac{\eta_{ins}}{K_{ins}} + \cfrac{\eta_{epoxy}}{K_{epoxy}}}$$

$$K_{axial} = K_{Cu}\eta_{Cu} + K_{ins}\eta_{ins} + K_{epoxy}\eta_{epoxy}$$

- Increasing the thermal conductivity of the potting material (epoxy) has a significant effect on thermal conductivity
- Wire insulation is a significant thermal choke
- Does ins the traditional wire insulation necessary with Litz wire-could it be replaced with the potting material

# Finite Element Analysis (FEA) of the High Voltage Insulation

High voltage insulation breakdown (> 2x operating voltage of the motor) is necessary between phases in a stator slot and between the conductor and back iron
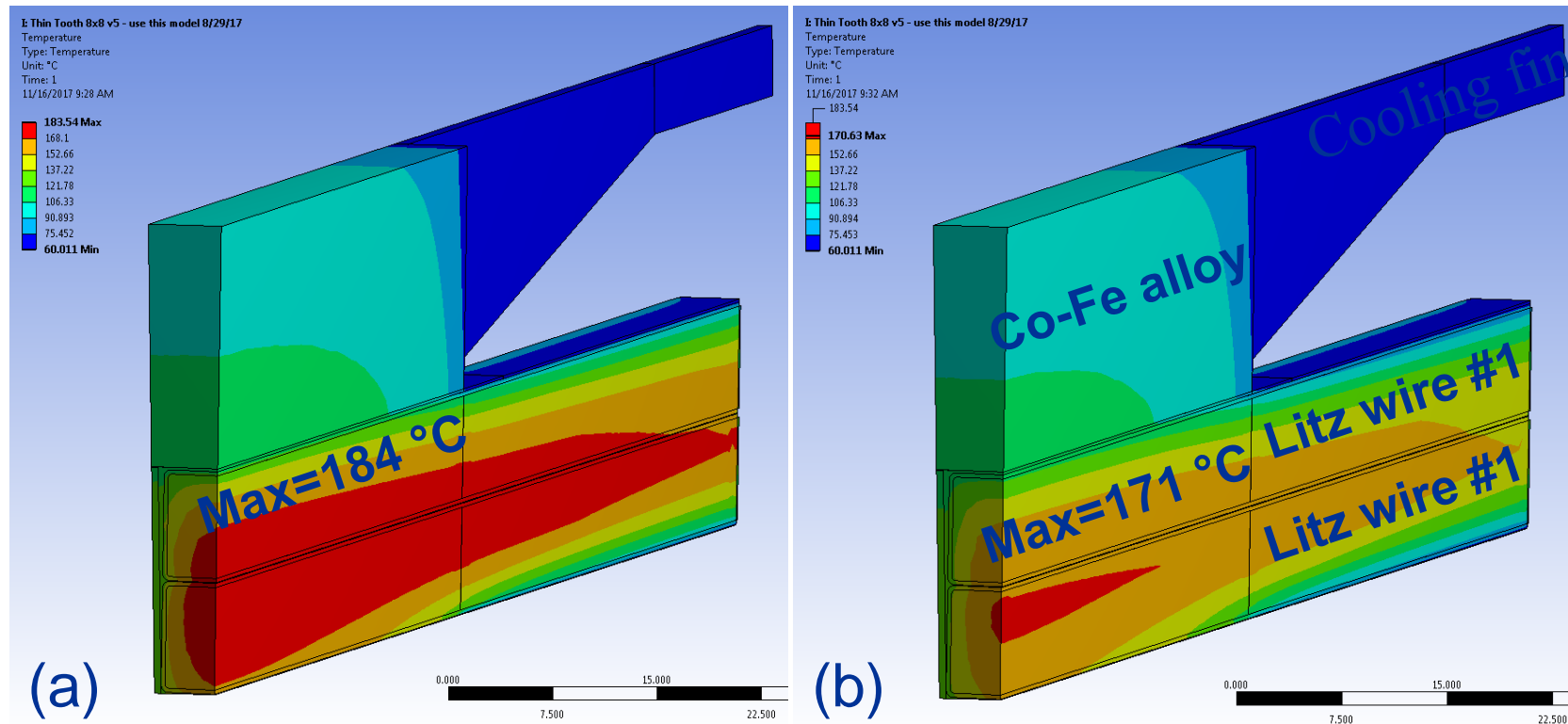
FEA of a theoretical motor slot. High voltage insulation wraps each Litz wire. High voltage insulation thermal conductivity (a) 0.12 W/m-K and (b) 0.24 W/m-K

Rudimentary Unit Cells (RUC)

RUCs allow for rapid reproduction of common (repeated) structures in a composite material

Hexagonal packing
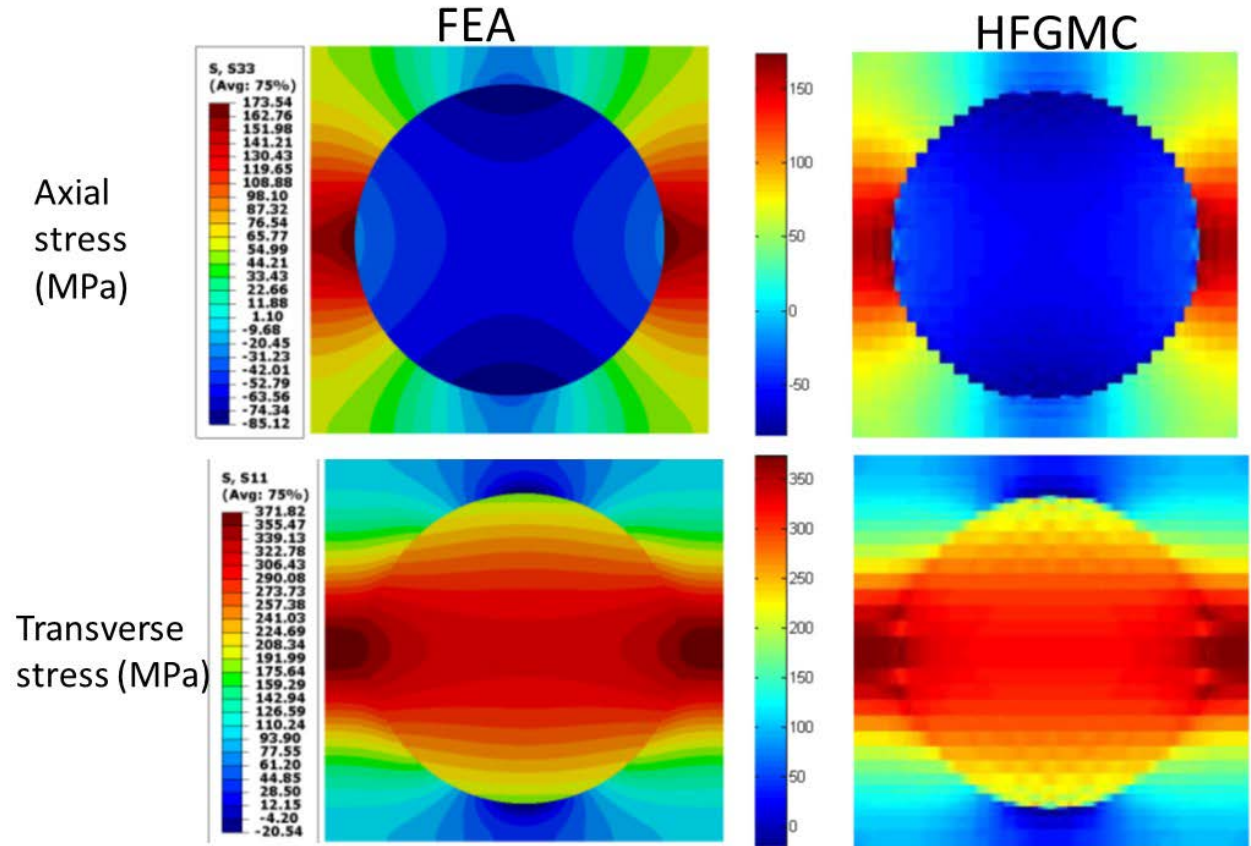
Rudimentary Unit Cell (RUC)

Square packing
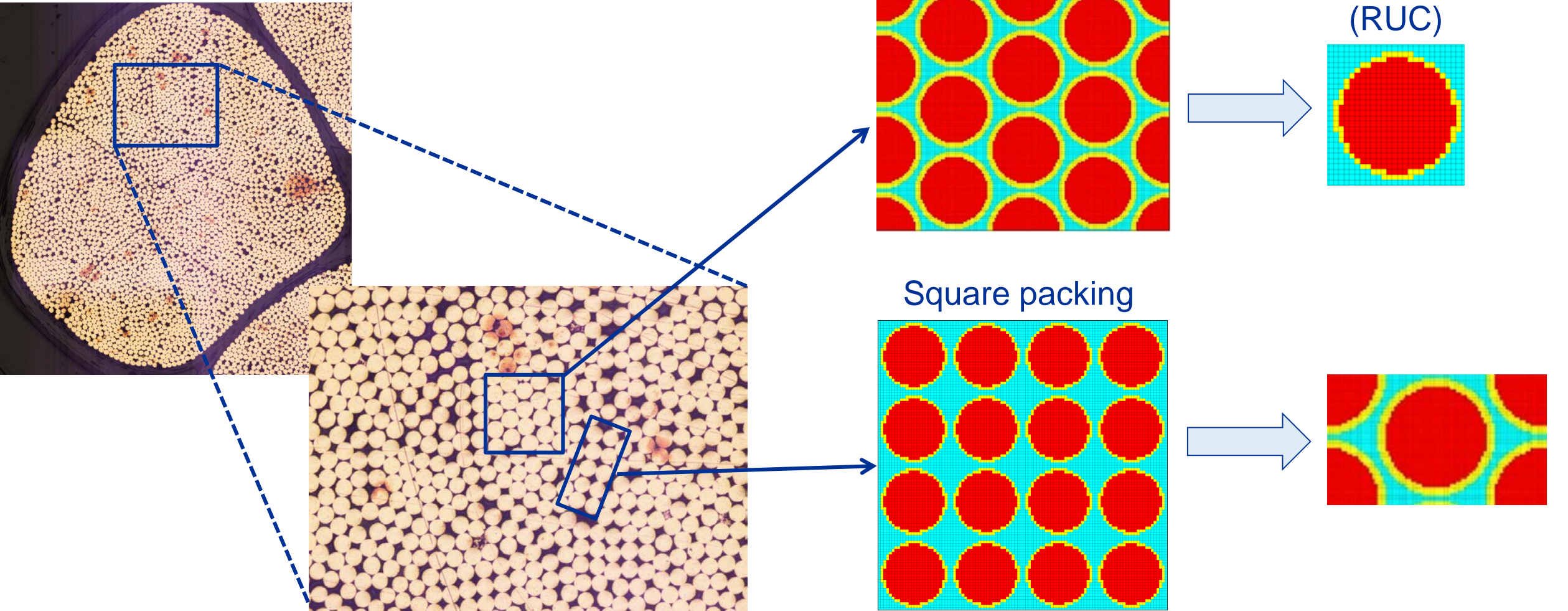
High Fidelity Generalized Method of Cells (HFGMC)

Provides a 10x increase in computational speed while minting most of the accuracy of FEA

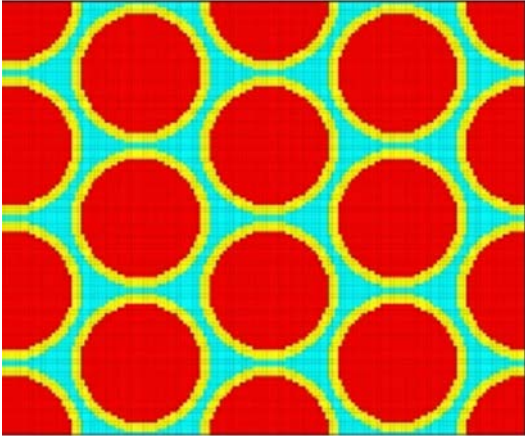Makes computations of large number of the repeated structures possible

Preliminary Micro Thermal Modeling Results

Hexagonal
Conductor ~ 55-60%
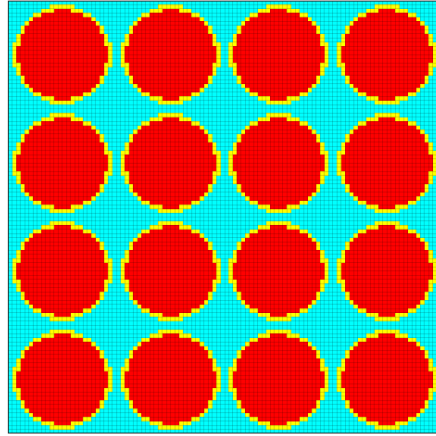Insulator ~20%-30%
Potting material~15-20%

Square
<<Place holder for
pickling factors>>

Random I and II
Conductor: 45-50%
Insulator: 20%-30%
Potting material: 25-30%

Square

Random-I

Random-II

$K_{\parallel} = 380$ W/m-K

$K_{\perp 22} = 0.79750$ W/m-K

$K_{\perp 33} = 0.79529$ W/m-K

$K_{\parallel} = 290$ W/m-K

$K_{\perp 22} = 0.86730$ W/m-K

$K_{\perp 33} = 0.86730$ W/m-K
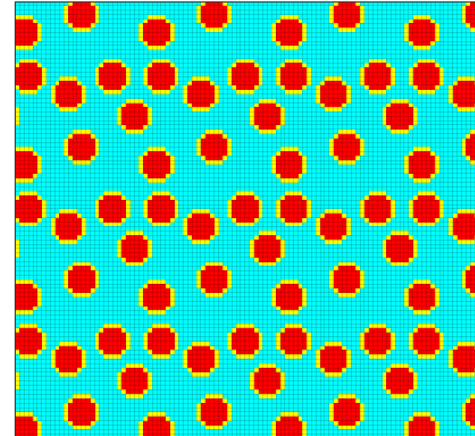
$K_{\parallel} = 240$ W/m-K

$K_{\perp 22} = 0.442$ W/m-K

$K_{\perp 33} = 0.421$ W/m-K
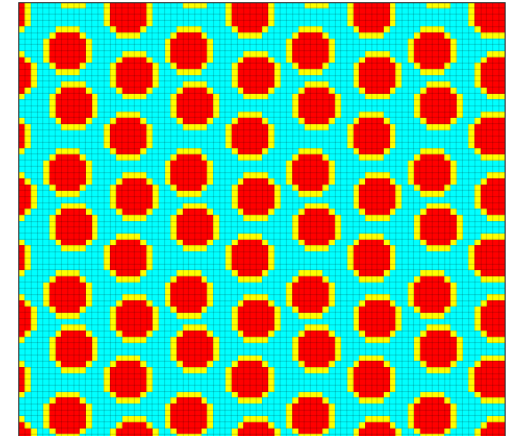
$K_{\parallel} = 255$ W/m-K

$K_{\perp 22} = 0.528$ W/m-K

$K_{\perp 33} = 0.524$ W/m-K

Summary & Conclusions

- Conceptualizing the insulation materials systems as composite is the key gaining to multi-functionality
  - Electrical
  - Thermal
  - Mechanical

- Composite approach provides modest, achievable goals can be set. thermal conductivities for

  - potting materials > 1 W/m-K, and

  - High Voltage Insulation ~ 0.5 W-m/K

  - possibly replacing or eliminating the insulation material on the Litz wire. These

  - goals are backed up by finite element modeling.

- Higher fidelity micro thermal modeling along with testing and model validation will bring more clarity to how the physical system behaves and will also refine the material development goals.

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Thank you!